

## Forecasting diurnal variations in fire intensity to enhance wildland firefighter safety

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**Abstract.** The extent to which the concept of displaying the diurnal variation in Byram's fire intensity on a daily basis during the fire season has been applied in the Province of British Columbia, Canada, to ensure safe and productive wildland firefighting work practices is described. This has been made possible by using the Canadian Forest Fire Danger Rating System coupled with fire weather forecasts and local information on the state of the fire environment in regards to fuel types, fuel moisture conditions and slope steepness. The resulting operational fire management tool has been the development, beginning in the mid 1990s, of the British Columbia Fire Weather and Behavior Advisory and Warning System. Potential areas for improvement in this system are detailed.

**Additional keywords:** advisories; British Columbia; Canada; Canadian Forest Fire Behavior Prediction System; Canadian Forest Fire Danger Rating System; Canadian Forest Fire Weather Index System; fire behavior; fire behavior prediction; fire danger rating; fire environment; fire weather; fire weather forecasting.

### Introduction

Safe and effective control of fire requires an ability to predict fire behavior which in turn is based on an understanding and assessment of the fire environment (Countryman 1966, 1972). Most changes in fire behavior occur as a result of fire moving over the terrain and as time passes.

The notion that wildland fire activity varies throughout the day as dictated by diurnal variations in fire weather conditions (Schroeder and Buck 1970), dead fuel moisture (Rothermel *et al.* 1986) and fuel temperature (Countryman 1966) is a relatively well-entrenched fact in wildland fire management circles as evident by its treatment in operational manuals and textbooks (Gaylor 1974; Moberly *et al.* 1979; Campbell 1995; Goodson and Adams 1998). These same principles have been translated into more integrated

measures of wildland fire potential in the form of fire danger indices (e.g. Fahnestock 1951; Brown 1964; Noste 1971; Alexander 1982b). Nonetheless, except for Beck and Trevitt's (1989) work, illustrating how quantitative measures of fire behavior vary diurnally has quite surprisingly not been a common practice.

De Groot and Alexander (1986) first introduced the concept of displaying equilibrium head fire intensities with the use of the Canadian Forest Fire Danger Rating System (CFFDRS). This paper provides an overview of the manner in which Byram's fire intensity is forecast diurnally, within the context of the CFFDRS. This process has been implemented in daily operations by the British Columbia Ministry of Forests for safe and productive wildland firefighting.

## Background

### *Byram's fire intensity*

The most basic characteristics of a free-burning wildland fire are that it spreads, it consumes fuel, and it emits heat energy (principally radiation and convection) and light in the form of a visible flaming combustion reaction. Byram's (1959) formula for calculating fire intensity, which he defined as the rate of heat energy release per unit time per unit length of fire front (regardless of its depth or width), incorporates these fundamental features:

$$I = Hwr, \quad (1)$$

where  $I$  = fire intensity (kW/m),  $H$  = net low heat of combustion (kJ/kg),  $w$  = quantity of fuel consumed in the active flame front (kg/m<sup>2</sup>), and  $r$  = linear rate of fire spread (m/s). Alexander (1982a) provides detail on how to calculate and interpret fire intensities.

Fire intensity thus defined can vary more than 1000-fold (i.e. 10–100 000 kW/m or more) and can be calculated for the head, back or flanks of the fire (Catchpole *et al.* 1992) or any portion of the fire perimeter. For practical purposes,  $H$  is generally considered a constant (~ 18 000 kJ/kg), and most of the potential variation in  $I$  is due largely to  $r$  rather than  $w$ .

Byram's (1959) fire intensity is directly related to flame size. While several empirical relationships exist linking fire intensity to flame length and height (Alexander 1998), the following rough rule of thumb is regarded as adequate for field use (after Newman 1974):

$$I = 300 L^2, \quad (2)$$

where  $L$  = flame length (m), which represents the distance between the tip of the flames and the midpoint of the flame front depth. The vertical height of a flame front determines the degree of radiant heat received at a given distance from the fire perimeter (Leicester 1985; Butler and Cohen 1998).

In spite of some limitations in Byram's (1959) fire intensity that have become apparent after some 40 years of use (Cheney 1990), it is still considered as extremely useful yardstick or index of fire behavior. Fire intensity is one of the major determinants associated with the difficulty of controlling or containing a free-burning wildland fire (Cole and Alexander 1995; Alexander 2000). Fire intensity dictates, for example, the likelihood of the initiation of a crown fire (Alexander 1998), the distance spot fires will be transported (Morris 1987), and whether or not existing or prepared barriers to fire spread will be breached (Wilson 1988b; Fogarty 1996). The occurrence of erratic or blowup fire behavior has been linked to fire intensity and certain atmospheric conditions aloft, including the existence of various complex fire-atmosphere interactions (Nelson 1993a, 1993b).

Fire intensity is also a factor that influences whether or not a house will survive the passage of a wildfire (Wilson 1988a). Intensity also determines certain fire impacts and effects such as the height of lethal crown scorch (Alexander 1998), which in turn affects post-fire tree mortality (Reinhardt and Ryan 1988).

In practice, fire intensities are sometimes expressed as a class or rank delineated on the basis of relatively distinctive differences in effectiveness of various fire suppression resources. Fire intensity class ranges 1 through 6 are most commonly used in support of fire management operations throughout Canada, Alaska and New Zealand (Alexander 1994; Alexander and Cole 1995; Taylor *et al.* 1997): <10, 10–500, 500–2000, 2000–4000, 4000–10 000, and >10 000 kW/m (the first two and last two classes may be combined at the discretion of the user).

### *The Canadian Forest Fire Danger Rating System*

The Canadian Forest Fire Danger Rating System (CFFDRS) as developed by the Canadian Forest Service is the accepted method or tool for predicting or forecasting fire behavior in Canadian forests (Stocks *et al.* 1989; Alexander *et al.* 1996; Van Nest and Alexander 1999; Alexander and Cole 2001). The CFFDRS comprises two major subsystems or modules (Fig. 1): the Canadian Forest Fire Weather Index (FWI) System (CFS 1984; Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Taylor *et al.* 1997).

The outputs of the FWI System consist of six relative numerical ratings for various aspects of fire danger for a reference fuel type (i.e. mature pine stand) on level terrain based on a continuous record of four weather observations (Turner and Lawson 1978) taken daily at 1200 hour local standard time (LST) or 1300 hour daylight saving time, namely dry-bulb temperature, relative humidity, 10-m open wind speed and 24-h accumulated rainfall. In turn, one basic calculation of the six standard FWI System components is undertaken each day and is designed to represent the peak fire danger conditions at around 1600 hour LST or 1700 hour daylight saving time, assuming a normal diurnal pattern (Van Wagner 1987).

While this once per day calculation is usually adequate for most daily preparedness planning purposes, there often exists the need to predict fire potential throughout the entire diurnal cycle or at least the main part of the burning period each day. As the moisture content of fine fuels, which is represented by the Fine Fuel Moisture Code (FFMC) component of the FWI System, experiences the greatest change from hour to hour, it becomes necessary to adjust the standard daily FFMC for time of day. The FFMC can be adjusted for time of day using the simple scheme devised by Lawson *et al.* (1996), or the more data-demanding hourly FFMC routine can be used to derive hourly FFMC values (Van Wagner 1977; Alexander *et al.* 1984).

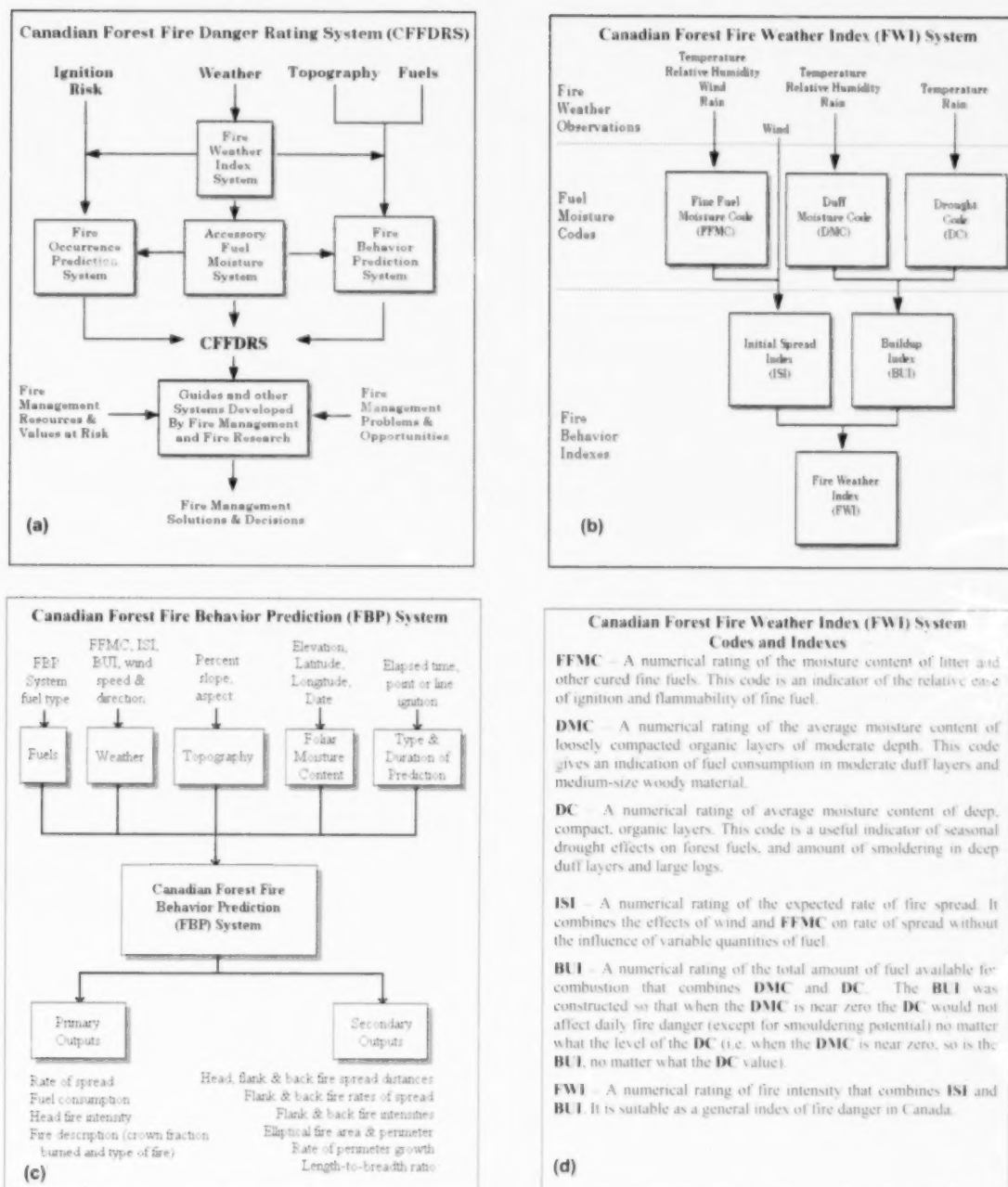


**Fig. 1.** Simplified structure diagrams for (a) the Canadian Forest Fire Danger Rating System illustrating the linkages to fire management actions (b) the Canadian Forest Fire Weather Index (FWI) System (c) the Canadian Forest Fire Behavior Prediction (FBP) System, and (d) the definitions of the six standard components of the FWI System (adapted from Canadian Forestry Service 1984; Forestry Canada Fire Danger Group 1992; Alexander *et al.* 1996).

In the FWI System, the daily moisture loss from the forest floor is reflected by two slow-reacting moisture codes (i.e. the Duff Moisture Code and the Drought Code), which also respond to changes in day length as the season progresses (Van Wagner 1987). Because calculation of the FWI System

components depends solely on weather readings and the time of year (i.e. month), they can just as easily be calculated from forecast weather as observed weather (Turner and Lawson 1978).

**Table 1. List of Canadian Forest Fire Behavior Prediction (FBP) System fuel types**

From Forestry Canada Fire Danger Group (1992). See Forestry Canada Fire Danger Group (1992) for written descriptions of each fuel type and De Groot (1993) or Taylor *et al.* (1997) for photographic examples

| Group/Identifier  | Descriptive name                        |
|-------------------|-----------------------------------------|
| <b>Coniferous</b> |                                         |
| C-1               | Spruce-lichen woodland                  |
| C-2               | Boreal spruce                           |
| C-3               | Mature jack or lodgepole pine           |
| C-4               | Immature jack or lodgepole pine         |
| C-5               | Red and white pine                      |
| C-6               | Conifer plantation                      |
| C-7               | Ponderosa pine/Douglas-fir              |
| <b>Deciduous</b>  |                                         |
| D-1               | Leafless aspen                          |
| <b>Mixedwood</b>  |                                         |
| M-1               | Boreal mixedwood-leafless               |
| M-2               | Boreal mixedwood-green                  |
| M-3               | Dead balsam fir mixedwood-leafless      |
| M-4               | Dead balsam fir mixedwood-green         |
| <b>Slash</b>      |                                         |
| S-1               | Jack or lodgepole pine slash            |
| S-2               | White spruce-balsam slash               |
| S-3               | Coastal cedar/hemlock/Douglas-fir slash |
| <b>Open</b>       |                                         |
| O-1a              | Standing grass                          |
| O-1b              | Matted grass                            |

The FBP System allows users to obtain a quantitative estimate of spread rate, fuel consumption, and fire intensity for potential fires that are either still accelerating or have in fact reached an equilibrium or steady state with their environment. The system also allows for a general description of the type of fire (i.e. surface, intermittent crowning, continuous crowning). A simple elliptical fire growth model is used to estimate the size (i.e. area and perimeter) and shape as well as the flank and back fire characteristics of fires that originate from a single ignition source. At present, 16 benchmark fuel types are recognised in the FBP System (Table 1). The FBP System takes into account the mechanical effects of slope steepness on fire spread and intensity (McAlpine *et al.* 1991), but a spot fire-weather forecast must be applied using techniques such as those described by Rothermel (1983) to account for mesoscale winds in complex terrain.

Two components of the FWI System, specifically the Initial Spread Index (ISI) and Buildup Index (BUI), are major inputs to the FBP System. The ISI and BUI are relative numerical ratings that incorporate the combined effects of short- (i.e. wind and fine fuel moisture content) and the long-term (i.e. moisture content of the fermentation, humus

and organic layers of the forest floor) weather conditions on potential rate of fire spread and fuel available for combustion, respectively.

Provisions are not currently made in the CFFDRS to directly account for certain meteorological conditions such as thunderstorm downdraft winds (Haines 1988), which are known to significantly affect wildland fire behavior. The fire weather forecaster can generally recognize the potential existence of these situations. Furthermore, coupled fire-atmospheric models that take into account the feedback effects of fire-atmosphere interactions (Clark *et al.* 1996; Reisner *et al.* 2000) have not yet developed to the point where they can be readily applied operationally.

### Operational development and use

On the evening of Wednesday, 20 July 1994, the Garnet Fire started in the Ellis Creek canyon, just outside of the municipal boundary of Penticton, British Columbia (Pattison 1995). The fire continued to spread towards the south-east between 20 and 24 July, despite the containment efforts of the British Columbia Ministry of Forests. Winds changed direction on 25 July and the fire spread rapidly, resulting in the evacuation of over 3000 people and the loss of 18 homes in the Upper Carmi subdivision. An independent review (Price Waterhouse 1995) of the management of this incident suggested that changes in the fire weather forecast were not applied to initiate the evacuation of the Upper Carmi soon enough. Neither were the potential implications of change in the wind communicated to residents to ensure they were apprised of the revised status of the fire.

As the Garnet Fire was being fought, news of the tragic loss of firefighters during the South Canyon Fire in Colorado (USDA/USDI/USDC 1994) and the potential implications of problems in the communication of anticipated changes in fire weather and behavior had reached British Columbia. Management sought change to prevent similar events from occurring in British Columbia.

In 1995, the British Columbia Ministry of Forests introduced a Fire Weather and Behavior Advisory and Warning System to ensure the safety of firefighters and to address weaknesses highlighted in the review of the Garnet Fire. British Columbia's Fire Weather and Behavior Advisory and Warning System (BCMFPP 2001) has evolved a great deal since its inception, and represents the first of its kind that has been implemented in Canada.

It is important to note that, although the federal Meteorological Service of Canada has a legal mandate for issuing public weather advisories, the responsibility for the issuance of fire weather advisories and warnings rests largely with provincial and territorial fire management agencies. Fire management agencies interpret weather information as part of a comprehensive assessment of the fire environment, fire management objectives and suppression capabilities.

The principles that guide British Columbia's Fire Weather and Behavior Advisory and Warning System state that fire management must anticipate wind events and extreme fire behavior, and apply this information to determine and implement appropriate suppression strategies and tactics. To ensure the safety of all line staff, this information must be communicated effectively to workers who may be at risk due to hazards associated with strong winds or extreme fire behavior.

#### *Wind advisory*

A Wind Advisory is issued when wind conditions are forecast to present hazards (e.g. windthrow, hazardous flying conditions for aircraft) or conditions that exceed safe limits for the transportation of workers. A Wind Advisory may be issued for: severe turbulence; strong winds; downbursts; or hail.

#### *Fire behavior advisory*

A Fire Behavior Advisory is issued when intensities in excess of Intensity Class 4 (i.e. >4000 kW/m) are forecast for a particular fuel type. Fire intensities in excess of 4000 kW/m will likely challenge direct suppression efforts.

#### *Extreme fire behavior warning*

An Extreme Fire Behavior Warning indicates that fire behavior is expected to exceed Intensity Class 4 for a particular FBP System fuel type. Moreover, conditions are expected to change or escalate rapidly in association with one of the following mesoscale-type disturbances: the passage of a cold front; a significant change in wind direction (i.e. >90°); severe localized thunderstorms and downdrafts; or the development of a low-level jet wind (Byram 1954).

#### *Operational procedures*

It is the responsibility of operational and key administrative staff including dispatchers to be aware of potential threats to field personnel and air operations. It is the fire control officer's responsibility to ensure that adequate advisories and warnings are issued. When personnel are dispatched to an area for which an advisory or warning has been issued, the dispatch information must include the advisory or warning. Incident commanders or project leaders must confirm their understanding of the situation and provide the dispatch centre with feedback on actual weather conditions and fire behavior characteristics.

Every advisory and warning must include:

- Type of advisory or warning issued;
- Date and time of issuance;
- Applicable geographic area (simple geographic description of the specific area affected);
- Expected arrival time and duration of disturbance;

- Description of conditions expected; and
- Details on who should receive copies of the advisory or warning and how it is to be distributed.

A Wind Advisory must include the type and intensity of disturbance (e.g. outflow winds gusting to 50 km/h). A Wind Advisory may be issued in the absence of aggressive fire behaviour.

A Fire Behavior Advisory must include the relevant FBP System fuel type(s). Issuing offices must adopt a format that highlights the period during which forecast conditions are expected to exceed Intensity Class 4.

In addition to the requirements of a Fire Behavior Advisory, an Extreme Fire Behavior Warning must include:

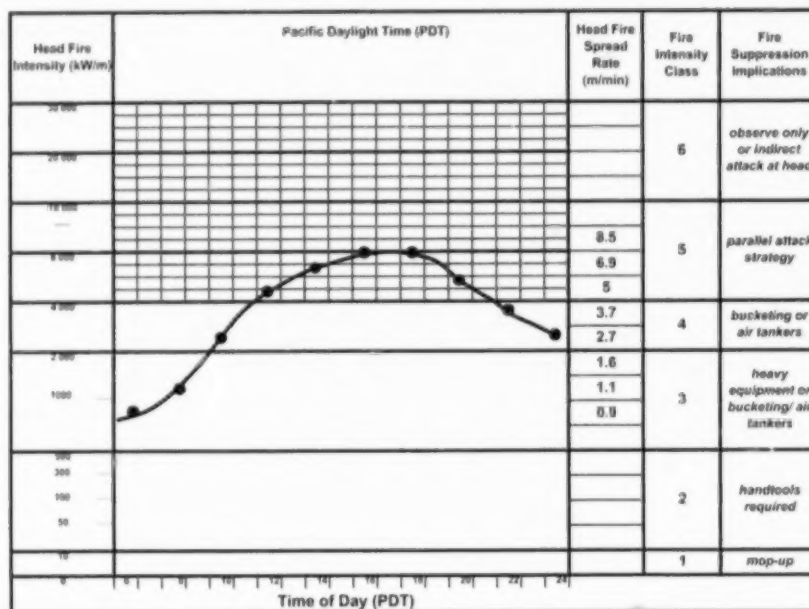
- Intensity of disturbance (e.g. 70 km/h winds from the south-west); and
- Expected effect on fire behavior (e.g. change in spread direction or fire intensity).

An Extreme Fire Behavior Warning must be issued independently of any other advisory, since these conditions pose the greatest threat to worker entrapment.

#### **Operational practices**

Diurnal intensity curves are produced daily in support of British Columbia's Fire Weather and Behavior Advisory and Warning System for both potential and actual ongoing fires. Weather inputs for solar noon are generated by a fire-weather forecaster, and these inputs are used to calculate forecasted daily FWI System codes and indexes for approximately 40 weather stations for each of six regional fire centres in British Columbia. A representative fuel type is chosen for each weather station. Diurnal FFMC values are generated using equations developed by Lawson *et al.* (1996), and the forecasted afternoon wind speed is applied for all hours of the day. One estimate of relative humidity is also required between 0600 and 1159 hours LST to apply the Lawson *et al.* (1996) diurnal FFMC model to the morning hours of the day. To reduce the number forecasted inputs required in support of synoptic advisories and warnings, the noon hour LST relative humidity is assumed at 1159 hours LST. It should also be noted that hourly inputs including mesoscale winds are generated in spot fire-weather forecasts when wildland fire behavior specialists make detailed predictions for a specific incident (Rothermel 1983).

When this process was first introduced, these data were entered manually into the FBP System software developed by REMSOFT Inc. of Fredericton, New Brunswick (<http://www.remsoft.com/index.html>), which is a Windows-based CFFDRS application that is available commercially. Graphs projecting fire intensity throughout the day were then drawn by hand (Fig. 2) and faxed to fire crew bases. Although illustrated here in black and white, the diurnal fire intensity class chart can also be color coded (Alexander and Lanoville 1989; Cole and Alexander 1995).

FIRE BEHAVIOR PREDICTION for 94-07-25ZONE/FIRE:  
Garnet FireFBP FUEL TYPE:  
C-7 Ponderosa pine/Douglas-fir

## NOTES:

Calculations are based on:

- ⇒ forecasted indices from Pentiction R/S Wx
- ⇒ 1300 hour PDT winds of 15 km/hr, and RH of 22 %
- ⇒ 1700 hour PDT FFMC of 95, and BUI of 152
- ⇒ assumption of level (no slope) ground

\*\* Fire behavior must be recalculated using on site conditions to account for any changes in fuel type, wind, and slope

|                                 |                                                                                                 |   |
|---------------------------------|-------------------------------------------------------------------------------------------------|---|
| ADVISORIES *                    | potential for intensities greater than 4000 kW/m exists                                         | * |
|                                 |                                                                                                 |   |
|                                 |                                                                                                 |   |
| EXTREME FIRE BEHAVIOR WARNING * | winds are expected to change direction from the northwest to the southwest after 1300 hours PDT | * |
|                                 |                                                                                                 |   |
|                                 |                                                                                                 |   |

Signed: Wildland Fire Behavior Specialist

Fig. 2. Sample diurnal fire intensity diagram generated in support of the British Columbia Ministry of Forests Fire Weather and Behavior Advisory and Warning System.

In May 2000, the reporting and graphics capabilities of WeatherPro3 software developed by REMSOFT Inc. were introduced to automate and simplify the process of generating diurnal fire intensity curves (Finn 2001). With this development, a line that depicts the critical surface fire intensity required to initiate a crown fire has also been added to the curves (Fig. 3). Weather information is forecast for the next 3 days, hence diurnal intensities can be generated for up to 3 days in advance, and forecast information and the graphs are updated daily. Graphs of diurnal fire behavior characteristics are now produced and posted on the British

Columbia Ministry of Forests intranet automatically, and these are emailed readily.

### Training

Wildland fire behavior specialists in Canada are now also trained to review the value and use of displaying fire behavior characteristics on a diurnal basis (ETC and CIFFC 2001). Students are asked to examine the implications of expected diurnal variation in head, back and flank fire rates of spread and intensities, on the potential for loss of life and property through the use of the 1985 Butte Fire (Rothermel

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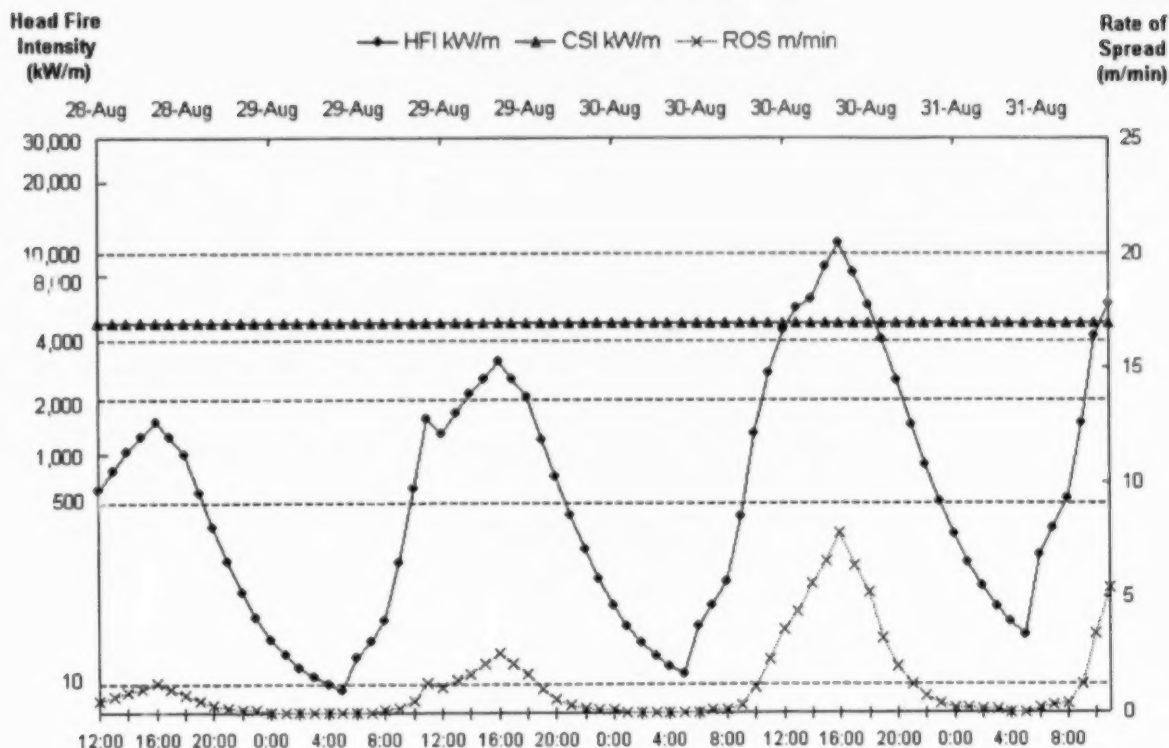


Fig. 3. Diurnal head fire intensities (HFI), head fire rates of spread (ROS) and the critical surface fire intensity required to initiate a crown fire (CSI) for FBP System Fuel Type C-3 (Mature Jack or Lodgepole Pine) are generated for up to 3 days in advance using FBP97 and WeatherPro3 software produced by Remsoft Inc.

and Mutch 1986; Alexander 1991) and 1994 Garnet Fire (Pattison 1995; Price Waterhouse 1995; Fig. 2) case studies.

#### Potential improvements

Several potential areas could be improved upon in order to increase the relative accuracy of the forecasted values. Fire weather forecasters should be required to provide more time-specific wind speed information than they would normally undertake for general forecast purposes, which is especially important for ongoing wildfires. Rather than simply applying the noon hour LST forecast wind speed, fire operations personnel should have the option to also apply a climatologically-based wind speed trend (Beck and Trevitt 1989) or automatically apply wind speed and direction predictions across the landscape from a microscale airflow model (e.g. Moore *et al.* 1998) or high-resolution atmospheric model (e.g. Gomez-Tejedor *et al.* 1999), and research has already been initiated in British Columbia in regard to the latter approach (Stull *et al.* 2002; <http://weather.eos.ubc.ca/FireStorm/>).

While the simplicity of using the Lawson *et al.* (1996) equations to estimate the FPMC for a given hour principally as a function of time of day is advantageous, the drawback with this method occurs when actual diurnal changes in temperature and relative humidity for a given day depart dramatically from the assumed diurnal trend. This could be overcome by utilizing the empirical modeling approach developed by Beck and Trevitt (1989) for predicting diurnal variation in temperature, relative humidity and wind speed given daily forecasted maximum and minimum values (which are routinely provided by fire weather forecasters), latitude and calendar date, coupled with the hourly version of the FPMC model (Van Wagner 1977; Alexander *et al.* 1984), at least during rainless periods when it is needed the most.

At present, the diurnal forecasted values in fire intensity are for a single representative point on the landscape but there is no reason that the same information could not also be displayed spatially with the use of geographic information system technology (Beck 2000; Lee *et al.* 2002).

## Concluding comments

The information and ideas contained in this paper depict an original application of wildland fire research and development to advance the safety and effectiveness of wildfire suppression operations. Moreover, in contrast to other fire weather advisories, watches, alerts and warnings (e.g. Gorski and Farnsworth 2000), the British Columbia Fire Weather and Behavior Advisory and Warning System is unique in that in addition to fire weather conditions it also takes into account considerations of the topographic (i.e. slope steepness) and fuel components (i.e. fuel load and moisture content) of the fire environment explicitly through application of the CFFDRS. While the concept of forecasting diurnal fire intensities has been applied in support of wildland firefighter safety, the same principles could easily be extended to other applications such as in assessing the length of the 'burning period' for daily preparedness planning purposes (Beck 2001).

Perhaps part of the hesitancy by wildland fire management organizations to forecast fire intensities and other physical fire characteristics on a diurnal basis can be traced to the inherent difficulty and uncertainty associated with predicting fire behavior (Rothermel 1983; Alexander and Lanoville 1989), especially in complex terrain and heterogeneous land cover. The point is acknowledged but hopefully through continued fire behavior training, including a review of the limitations and assumptions involved in tools and products like the CFFDRS and fire weather forecasts, this situation can be remedied. Such training is equally important to ensure that users do not apply the kind of outputs illustrated in Figs 2 and 3 blindly, without a comprehensive assessment of the forecast, the fire environment, fire management objectives and suppression capabilities.

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